Fractures and Their Distribution in the Tills of Ohio[1]

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Abstract. Fractures in till may be horizontal, parallel high- to low-angle, or polygonal (when viewed on a horizontal surface). They have been attributed to several geologic processes, the most important of which are desiccation, freeze-thaw, glaciotectonics, and lodgement till deposition. A literature review, a field study, and core examinations have identified many areas in Ohio where fractures are relatively common. All types of fractures are present within the state, but the depths, relative abundance of types, and their concentrations differ among physiographic regions.

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INTRODUCTION

Bedrock fractures, which include joints, fissures, and cracks, have been a popular topic of geologic investigation for more than a century. Fractures have been observed in unconsolidated materials in Ohio for at least that long (Read 1880); however, their investigation has lagged far behind their more brittle counterparts, and for good reason. Joints or fractures in rock could be interpreted to answer important geologic questions of the day such as the alignment of local and regional tectonic stresses as well as practical questions such as the prediction of the sizes of granite blocks at increasing depths in the quarries of New England (Jahns 1943). Fractures in unconsolidated materials, however, have been an overlooked curiosity until relatively recently, when hydrogeologists began interpreting leakage through clayey unconsolidated aquitards as the result of naturally occurring openings in otherwise low-permeability materials. Fractures in unconsolidated sediments (commonly called *joints* in the literature of Pleistocene geology) have been related to a number of other geologic phenomena, including slope failures in till (McGowan and Radwan 1975; Highman and Shakoor 1998), lacustrine sediments (Babcock 1977), and loess (Bradford and Piest 1980). Harrell and others (1991) suggest fractures in till are responsible for radon gas movement in areas having less than 6 m (20 ft) of clayey drift over radon-producing shale. For modern society, fractures in till have become a health issue. Many of our facilities and activities rely on relatively impermeable clayey sediments in their natural state to protect surface and ground water from a multitude of contaminants. Fractures in surficial materials affect aquifer sensitivity and pollution potential; however, fracture types and distribution are generally not considered when modeling ground water flow—an unhealthy situation for ground water consumers.

Fracture studies in unconsolidated materials in Ohio are in their infancy. Fractures in Ohio till and other fine-grained materials are common, but that simple statement would have been widely questioned just a few years ago. Today the questions are: how are fractures formed, are they ubiquitous at the surface, and are they common in the subsurface? The purpose of this paper is multifold: 1) to provide a concise review of fracture processes and occurrence in unconsolidated deposits, 2) to compile the locations of recorded fractures in Ohio tills, 3) to investigate fractures in till cores and a large test pit in Ohio, and 4) to model the distribution of fractures in Ohio tills based on facies, geomorphic setting, and physiography.

FRACTURE PROCESSES AND OCCURRENCE

Mechanics of fracturing

The field of mechanics of materials provides a useful way to study fractures in rock and brittle unconsolidated materials. In a mechanical view of materials, a deposit's reaction to stress is considered with little regard to its other physical or chemical properties, properties which are important in other aspects of the geology of fractures and which will be discussed later.

Pollard and Aydin (1988) summarized the geometry and mechanics of fracturing in rock. Their preferred definition of fractures (a general term that includes joints, fissures, and cracks) was first proposed by Woodworth (1896) and stresses the geometry rather than the genesis of fractures. According to this definition, joints are fractures that gape so as to preserve plumose or feather structures. Klint and Fredericia (1998) agreed and applied the definition to unconsolidated sediments, adding that fractures are larger than the grain size of the sediment and generally lack shear displacements. Fractures that have shear displacements develop slickensides rather than plumose structures and are more properly termed microfaults and shears. Plumose structures, however, are rare in the weathered zone of unconsolidated sediments owing to alteration.

Modern concepts of the mechanics of materials, including unconsolidated geologic materials, have led to a number of conclusions about the growth of fractures (Pollard and Aydin 1988). For example, in a homogenous material, fractures initiate at flaws such as pebbles or fossils that naturally perturb the stress field in such a way that the sum of local stresses at the flaw exceeds the tensile strength of the material. Fracture growth is incremental and a result of stress conditions at the fracture

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tip. Theoretical models of fracture growth suggest that when two fractures of unequal length are subject to equal driving stress, the longer fracture will lengthen first. In a varying stress field among equal-length fractures, those subject to the greatest stress will lengthen first. As a collection of fractures develops, the energy available for fracture propagation is used to form longer fractures at the expense of shorter ones, thus offering a partial explanation for the common observation that fracture frequency decreases with depth (McKay and others 1993; Jakobsen and Klint 1998). The natural heterogeneity of geologic materials results in growth that leaves smooth to twisted fracture planes. Fractures may terminate at a boundary with a stiffer medium or a region of greater compressive stresses. Fractures can grow across a bedding plane if there is cohesion between the surfaces such as that provided by high friction or high normal stress.

Fractures grow as a function of time as well. A common observation of stratigraphically older materials, especially tills, is that fractures are more common and more developed than in younger deposits (White and Totten 1982; Kirkaldie 1988). As stress and material conditions change through time, as they do during diagenesis, fractures may periodically arrest or grow.

There is a growing body of field observations of fractures in unconsolidated deposits. These observations note physical and, to a lesser extent, chemical characteristics of fractures. Observations have led to a host of interpretations about the particular geologic processes responsible for the stresses that induce fracture formation. These studies identify three major forms of fractures in unconsolidated materials: 1) vertical fractures, which decrease in frequency at depth and join to form polygons when viewed on a horizontal surface; these are attributed to desiccation and freeze-thaw processes; 2) horizontal and subhorizontal fractures, which also become less frequent at depth; these are attributed to desiccation, stress release, shear, and freeze-thaw processes; and 3) high- to low-angle fractures that show little change in frequency, may show displacement, and do not join to form polygons; these are attributed to shearing or lateral stress release. Important and historic fracture studies are summarized below.

Fractures in Fine Grained Unconsolidated Materials

The ever-curious G. K. Gilbert (1882) noted streams on the floor of Salt Lake Desert, Utah that followed fractures in unconsolidated clay. The presence of fractures surprised him because he associated fractures with rocks and not soft, laminated clays and marls; Gilbert asked his readers for an explanation of their occurrence. LeConte (1882) responded, stating he believed desiccation to be the operative mechanism and suggesting that it also explained deep cracks in thick overbank deposits of the Sacramento River in California. These cracks were up to 18 m (60 ft) deep and connected to form surface polygons 3.0-5.0 m (10-15 ft) across.

Babcock (1977) studied sets of fractures in Pleistocene lacustrine deposits in central Alberta. The sediments developed sets of fractures parallel and normal to steep outcrop faces, and there was no correlation of directional trends between fractures in rock and those in lacustrine materials. Babcock suggested the fractures did not originate from above but from lateral stress release as a result of stream valley erosion and desiccation processes. He also believed the fractures did not penetrate more than a few meters into the outcrop face and had little control on regional ground water movement.

Benson and Othman (1993) investigated the formation of horizontal partings or fractures in a large cylinder of compacted clay that experienced freezing and thawing while buried on the campus of the University of Wisconsin-Madison. Measurements showed that as freeze-thaw cycles progressed through the winter, the clay dried and water accumulated as ice in thin, horizontal bands above the freezing front. Water migrated from as much as 50 cm (20 inches) below the freezing front toward the thin ice lenses; vertical desiccation cracks formed below the freezing front. Thickness and spacing of ice lenses depend on freezing rate and soil saturation (Penner 1960). Ice lenses are thinner and less frequent at depth, where the freezing rate is moderated and overburden pressure is greater. Macroscopically, thawed soil exhibits parallel horizontal partings or fractures many centimeters long and up to 2.0 cm apart; the partings decrease in frequency from near-surface to several decimeters below the local frost line, beyond which they are absent. Besides partings, several microscopic sedimentary structures are attributed to freeze-thaw processes (Mermut and St. Arnaud 1981).

Fractures in Till

Till, by far, is the most common and most complex suite of glacial deposits. Its composition is a reflection of the materials it has overridden, and its physical characteristics relate to the dynamics of active ice and to the processes of stagnant or wasting ice. A better understanding of the geology of fractures in till has slowly developed in the last few decades from a handful of important papers that have discussed fractures in undifferentiated till, newly formed till, lodgement till, water-laid till, and buried till.

Grisak and others (1976) considered fractures ubiquitous in all but the youngest tills in Canada's Interior Plains. He suggested a laundry list of geologic causes for fractures in till, each with potential for creating fractures with different characteristics. For example, fractures may develop by desiccation, freeze-thaw cycles, shearing from overriding ice, stress relief from removal of glacial ice, crustal rebound, regional tectonic stresses, and volume change from geochemical processes. Klint and Fredericia (1998), working in Denmark, supplied a similar listing of geologic causes for fractures. Loading and shearing-related mechanisms create fractures that have a dominant trend (systematic fractures; see Connell 1984; Helmke and others 1998), whereas desiccation and freeze/thaw develop fractures without a dominant trend (nonsystematic fractures; see McKay and others 1993). In an example from northwestern Pennsylvania, Cox and Harrison (1979) suggested that fractures in till propagated from underlying fractures in rock.

Ballantyne and Matthews (1983) documented polygonal fracture development on a newly exposed till sheet in the periglacial environment in front of a retreating glacier where the mean annual temperature was -1° to -2° C (30-28° F). The well-documented retreat has exposed flat-lying sandy till (32% silt and clay) 1.0-2.0 m (3-7 ft) thick overlying metamorphic bedrock. Cracks within 30 m (98 ft) of the snout, an area deglaciated less than 4 years, are shallow (less than 20 mm [about an inch] deep), narrow (less than 20 mm wide), and short (less than 1.5 m [5 ft] long) and do not form polygons. In the oldest area, deglaciated for 35 years, cracks are 30-55 mm deep by 20-60 mm wide (1.2-2.2 inches by 0.8-2.4 inches) and form polygonal networks; individual polygons measure 0.2-0.4 m across (8-16 inches). Between the old area and the snout, crack networks pass through transitional forms. Fracture width and depth were shown to increase exponentially for 35 years with no sign of leveling off. Surface clasts migrate via surficial processes to the cracks and fill them. Evidence suggests that the cracks formed by desiccation and that migration of clasts continues until vegetation is established.

Jakobsen and Klint (1998) investigated fractures in clayey lodgement till in Denmark. They categorized fractures into four sets based on orientation and character. The first set was large, straight, and nearly vertical, and had a uniform strike, nearly uniform spacing (about 0.6 m [2 ft]), and a nearly uniform fracture frequency until they were no longer present at a depth of 8.0 m (26 ft). These fractures were interpreted to be the result of loading from an overriding glacier within lodgement till. A second subvertical set was less well developed, having an irregular, rough-surfaced trace and more random orientation. Fracture-trace frequency was high at the surface and decreased quickly until fractures disappeared at a depth of 4.5 m (15 ft). The authors were uncertain of their origin. The third set was primarily horizontal, filled with silt and fine sand, and had a relatively uniform spacing with depth. These fractures were interpreted as glacial (lodgement) shears formed as sub-ice debris was lodged in sequential, thin horizontal sheets during the accumulation of lodgement till. The final set, also horizontal, was concentrated near the surface and intersected numerous vertical fractures; these fractures may have formed by freeze-thaw processes.

Two Canadian studies (McKay and others 1993; McKay and Fredericia 1995) of water-laid till considered the problem of determining fracture width and also expanded upon the role of dry climate in deepening fractures. The clay-rich (25-45% 2.0-micron clay) St. Joseph Till is a water-laid till at Sarnia, southwestern Ontario, about 160 km (100 mi) northeast of Toledo, OH. The till is weathered and fractured to at least 6.0 m (20 ft). At these depths, fracture width or aperture is expected to be small and not directly measurable because of sampling disturbance. Hydraulic fracture aperture was estimated from hydraulic conductivity measurements in the field. Most aperture values (90%), including those at depth, were determined to be about 21μ wide; a few wider apertures (21-43μ) occurred in the upper 3.5 m (11 ft). Fractures at depth were identified by staining on a surface, the presence of roots (which decreased downward), and a tendency of till to part. Fracture spacing decreased downward such that at 1.0 m (3 ft) depth, 80 fractures could be counted crossing a horizontal line 2.0 m (6 ft) long; however, at 6.0 m (20 ft) only one vertical fracture would cross the same distance (McKay and others 1993). McKay and Fredericia (1995) noted a N-S and E-W preference to the fractures at Sarnia but interpreted the trend as preferential opening of a pre-existing subset of fractures reacting to local stress release parallel to the face of the excavation. They proposed a conceptual model of fracture formation at the site that is based on changes in the ground water table during the Middle Holocene. The site is near Lake Huron and likely experienced a lowered ground water table until about 6,000 years ago at the end of the dry Altithermal period, when lake and ground water levels were lower throughout the Midwest. Stresses from drying and shrinking in both vertical and horizontal directions formed new and deeper fractures.

Fractures not only originate from the modern surface, but also may extend downward from buried surfaces. Helmke and others (1998) recognized a fracture pattern in older pre-Illinoian loam till in Iowa in which fractures were polygonal and extended throughout a 33 m (108 ft) section exposed by quarrying. The fractures, likely from desiccation, are associated with several paleosol horizons developed in interglacial times (M. F. Helmke 1999, personal communication). Hildebrandt (1998) noted polygonal fractures in a till unit in Denmark, sandwiched between two other tills. The polygonal fractures were interpreted to have formed when the till's surface was exposed to weathering during a short periglacial period between two minor glacial advances.

MATERIALS AND METHODS

Information was collected from three main sources to determine the distribution and types of fractures in Ohio tills. First, historic references of fractures in Ohio tills (and other unconsolidated materials) were compiled from published and unpublished reports of the Ohio Division of Geological Survey (DGS) and from discussions with the surficial geology mapping staff and others. Since the 1960s, geologists have mapped the Pleistocene geology of many Ohio counties with a goal of understanding regional stratigraphy. Documenting fractures was not a goal of any study; however, their presence was noted in many reports.

Secondly, fractures were described from a large test pit at the Molly Caren Agricultural Center of The Ohio State University in Madison County, about 33 km (20 mi) west of Columbus. The site lies in the Southern Ohio Loamy Till Plain physiographic section (Brockman 1998) (Fig. 1), in Wisconsinan-age till (Fig. 2). The pit was constructed to demonstrate several aspects of fractures in till. The test pit site was considered typical for the till plains and likely to contain many of the fracture features observed in till cores and referenced in the literature. Christy and others (2000) review the

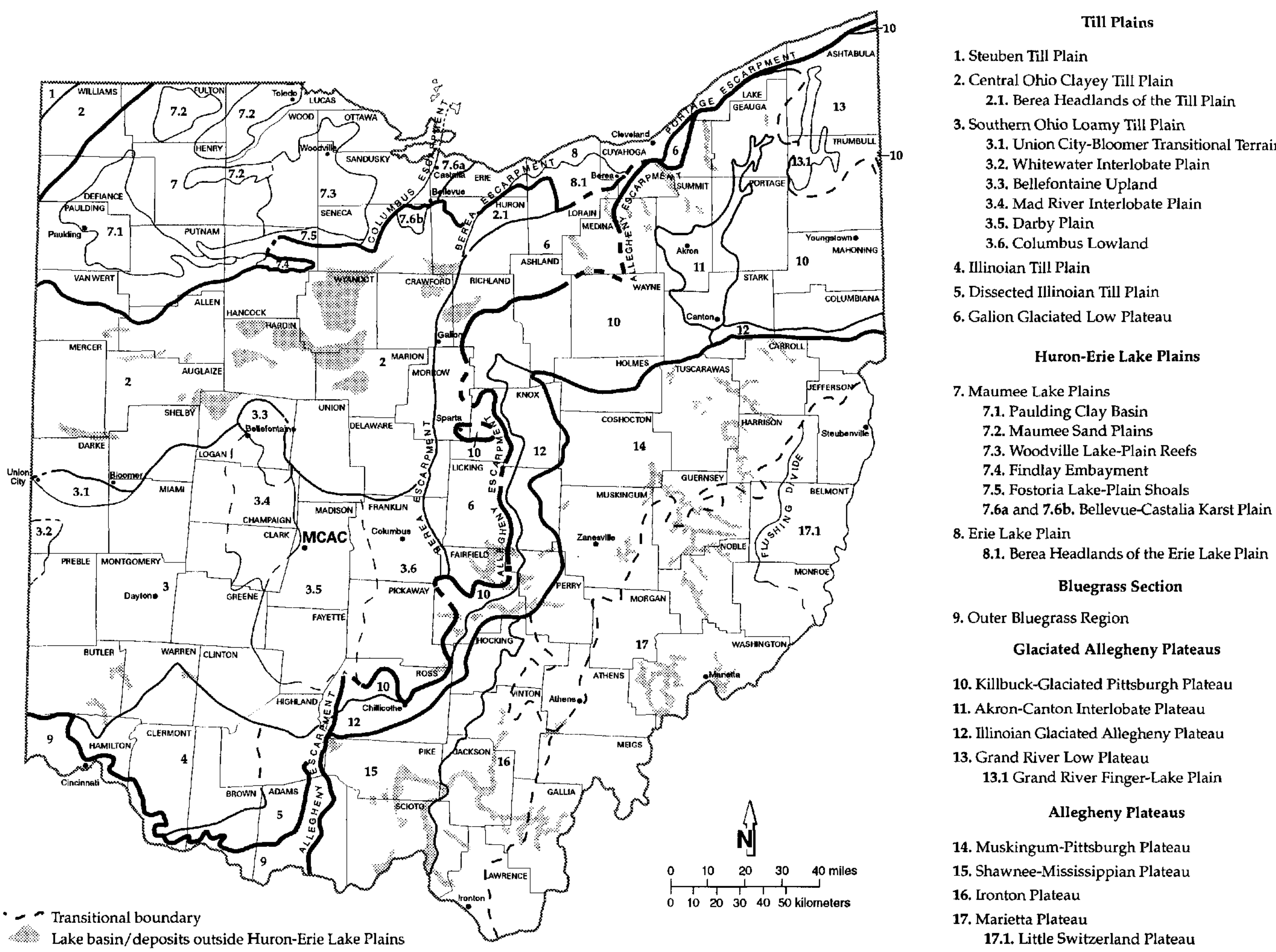

FIGURE 1. Physiographic regions of Ohio. Regions, subregions, and major escarpments are natural boundaries that separate areas of predominantly different geology, geologic history, and regional fracturing patterns. MCAC, Molly Caren Agricultural Center. Modified from Brockman (1998).

design and construction of the test pit, which measured 25 m × 9 m × 3 m deep (84 ft × 30 ft × 12 ft). Fausey and others (2000) report on hydrogeologic and chemical properties of the till and fractures in the pit. Christy and Weatherington-Rice (2000) discuss the implications of an educational workshop held at the test pit.

The test pit was located on a slight hummock (less than 1.5 m [5 ft] of relief) that has been mapped as one of the northernmost elements of the London Moraine, a low, recessional moraine (see Fig. 3). Late Wisconsinan-age Darby Till, a silt loam till deposited about 16,700 years BP (Quinn and Goldthwait 1985), is the surface material within which a shallow, moderately well drained soil (Lewisburg) has developed. The site overlies a large, deeply buried bedrock valley, most of which is filled with Late Wisconsinan drift (Lloyd and Szabo 1997). Bedrock at this location is about 70 m (225 ft) below the land surface.

In a preliminary investigation of the site, a 3.8 cm (1.5 inch) diameter Giddings soil probe retrieved a sample from a depth of about 1.5 m (5 ft) that contained a fracture trace. Plans were then undertaken to dig a large test pit in the vicinity. Over the course of 4 days in late August 1997, the sides and benches of the test pit were prepared using knives and trowels to allow fractures to be seen, described, and tested.

The third source of data was cores from the DGS core repository. In the late 1980s, DGS augered 25 undisturbed cores for stratigraphic studies using a continuous sampling system. The 24 cores that contained till (Fig. 3) were evaluated for the presence of fractures. The air-dried, 5.0-cm (2.0-inch) diameter vertical cores were split into 15-cm (6.0-inch) longitudinal sections with a hydraulic core splitter at 0.3-2.5 m (1.0-8.0 ft) intervals. They were described noting lithology, fracture depth and geometry (horizontal, vertical, or angled), as well as the geomorphic setting of the core site. Fractures were considered horizontal (within 10° of 0°) or vertical (within 10° of 90°); angled fractures fell between those values. The geomorphic setting of the core sites was determined from analysis of topographic maps and from the literature. Core sites were on lake plain, ground moraine, and several types of ridge moraine: recessional moraine (St. Johns Moraine), end moraine (Powell Moraine), and superposed (palimpsest) moraine (Broadway Moraine). These geomorphic settings are relatively common in the state. The dominant lithologies of the cores range from silty

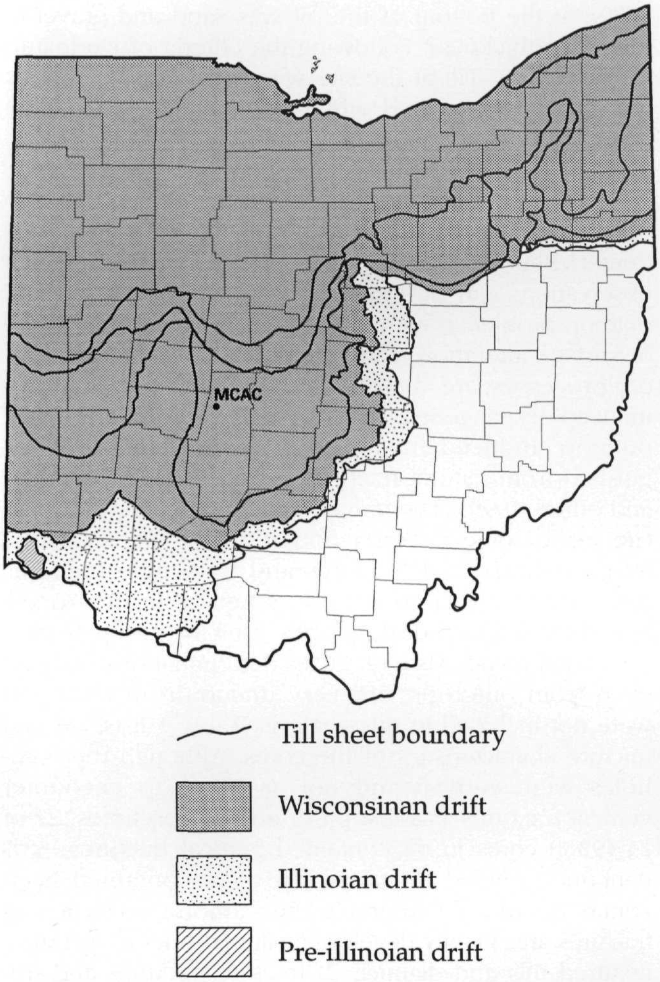

FIGURE 2. Boundaries of major Wisconsinan and earlier ice sheets in Ohio. Surficial Wisconsinan till sheets differ in age and lithology from north to south, and are marked by well-formed end moraines. MCAC, Molly Caren Agricultural Center. Modified from Ohio Division of Geological Survey (1997).

clay till to loam till and stratigraphically are named (from youngest to oldest) Hiram and Hayesville Tills (Late Wisconsinan), and upper, middle, and lower Millbrook till (Illinoian age). The cores were compared using simple statistics to note relationships among fractures, lithology, and physiography.

RESULTS

Although fracture information found in Ohio's geologic literature is more general than that from either core records or the test pit, it covers a much wider geographic area. Fractures in unoxidized till have been recorded in published reports and field notes from at least 37 Ohio counties (Fig. 4), which include every surficial Illinoian and Wisconsinan till unit on the *Quaternary Geology of Ohio* map (Pavey and others 1999). The locations of these records reflect areas of DGS mapping projects, rather than an actual absence of fractures in counties not listed. These fractured-till units represent a great variety of ages, facies, and textures, including Wisconsinan- and Illinoian-age tills and lodgement, melt-out, water-laid, and wave-planed tills that range from clay loam to loam. Tornes and others (2000) discuss the range of textures of fractured Ohio soils that have developed from parent materials of till and other unconsolidated deposits. White and Totten (1982) noted that in northeastern Ohio, fractures in older tills are much more strongly oxidized and have a greater variety of geometries than Late Wisconsinan tills, which have closely spaced polygonal fractures.

The test pit provided a three-dimensional view of fractures that was unavailable in the Ohio literature, yet matched descriptions from elsewhere (near-surface horizontal fractures, though present, were not evaluated at this site; see Tornes and others 2000). The fractures were polygonal in plan view and primarily vertical on vertical surfaces. Figure 5a,b,c summarizes aspects of

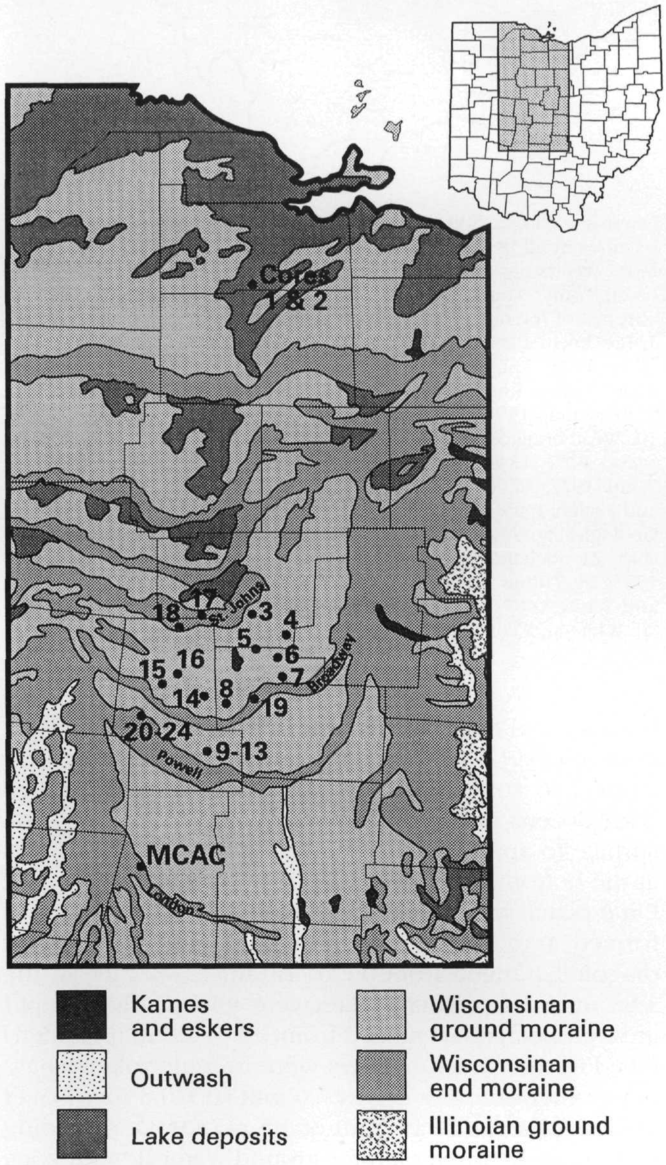

FIGURE 3. Locations of the Molly Caren Agricultural Center (MCAC), central and northern Ohio till cores, and associated glacial features and deposits. Sites 1 and 2 are on the Maumee Lake Plains, just 4.6 m (15 ft) from each other. The rest of the sites are in the Central Ohio Clayey Till Plain region of the Till Plains. Sites 9-13 are 9.2 m (30 ft) apart, and sites 20-24 are 4.6 m (15 ft) apart. Modified from Ohio Division of Geological Survey (1997).

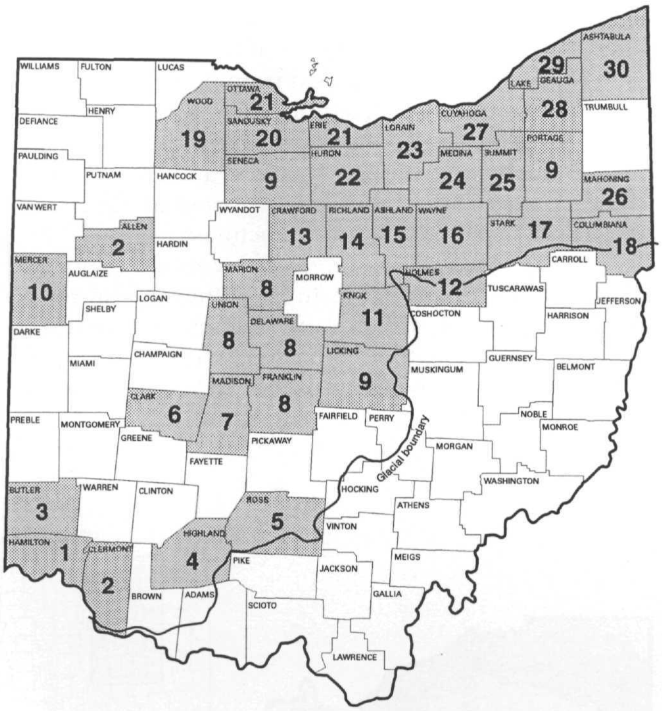

FIGURE 4. Distribution of the published and documented locations of fractures in till in Ohio. In some publications, specific sites are noted; more commonly, however, references to fractures are generalized to county only. The lack of data in any county does not indicate an absence of fractures, only that no data are available for that county. 1. Brockman 1983; 2. Brockman file data; 3. Goldstein 1968. 4. Rosengreen 1974; 5. Quinn and Goldthwait 1985; 6. Weatherington-Rice 1998; 7. Brockman and Szabo 2000 (documented in this study); 8. Brockman 1994; 9. Michael Angle 1999, personal communication; 10. Weatherington-Rice 1999, personal communication; 11. Viani and Szabo 1987; 12. White 1973; 13. Totten 1987; 14. Totten 1973; 15. White 1977; 16. White 1967; 17. DeLong and White 1963; 18. White and Totten 1985; 19. Blevins and Wilding 1968; 20. Ohio Division of Geological Survey core record 3051, Sandusky County, Ballville Township; 21. Richard Pavey 1999, personal communication; 22. Totten 1985; 23. Totten 1989; 24. Totten 1988b; 25. White 1984; 26. Totten and White 1987; 27. Ford 1987; 28. Totten 1988a; 29. White 1980; 30. White and Totten 1979.

fractures and fracture polygons in both oxidized and unoxidized Darby Till. Fractures on a vertical surface were vertical to subvertical and their frequency decreased from dozens per horizontal meter (3.0 ft) near the soil surface to approximately one or two per meter (3.0 ft) at the bottom of the test pit (3.2 m, 12 ft) (see Fig. 5a). On a planar bench in the pit at 1.06 m (3.5 ft), fractures formed 4- to 7-sided irregular polygons; their largest diagonals ranged from 0.7 to 1.0 m (2.3-3.2 ft). At the 1.86 m (6.1 ft) bench, there were fewer polygons per area, and diagonals ranged from 1.0 to 2.0 m (3.2-6.5 ft) (see Fig. 5b). Fracture faces were irregular planes having a relief of about 2.0 to 7.0 mm (0.1-0.3 inch) over an area of 1 cm^2 at a depth of 1.5 m (4.9 ft), providing a moderately rough path for ground water flow. A zone of white secondary carbonate precipitate about 1.0 to 6.0 mm (0.04-0.25 inch) thick coated fractures (see Fig. 5c).

Plumose structures could not be seen on fracture faces. Low- to high-angle fractures with offsets also were not noted. Darby Till in the pit was remarkably uniform in appearance and texture (see Fausey and others 2000); at the bottom of the pit was sand and gravel of unknown thickness. Following the criteria of Dreimanis (1989), Darby Till at the site was considered a sub-ice melt-out facies formed while stagnant ice melted upward from below.

Some fracture patterns that are noted in the DGS cores of central and northern Ohio are similar to those observed in Darby Till at the Molly Caren Agricultural Center. Benefits of studying fractures in cores are that observations can be much deeper than a test pit, and outcrop problems, such as incomplete vertical exposure or surface alteration from recent freeze/thaw and wet/dry processes, are absent. On the other hand, fractures induced by augering or core splitting are absent in outcrop. Induced fractures, however, can be distinguished from natural fractures in most cases (Kulander and others 1990). The limited lateral exposure in a core can make some interpretations difficult. For example, irregular horizontal fractures and low-angle fractures can appear the same in core, whereas in outcrop, a low-angle fracture distinguishes itself by rising from a horizontal plane. Also, till facies determinations, difficult even from outcrops, are very uncertain in core and were not included in this analysis. Table 1 lists site and fracture characteristics of the cores. Although the coreholes were vertical and not as likely to encounter vertical fractures as a test pit or angled coreholes, 22 of 24 (92%) cores in till contained vertical fractures, 38% contained angled fractures, and 96% contained horizontal fractures. General trends among all types of fractures are: 1) they develop in silt and fine- to medium-textured tills and diamict; 2) fracture aperture and frequency decrease with depth; 3) most fractures below about 6.0 m (20 ft) appear closed when viewed with low magnification; and 4) fractures are deeper in ridge moraines than ground moraine.

Horizontal fractures in the cores may be divided into three sets: 1) a near-surface, closely spaced (high-frequency) set, 2) a high-frequency set in a deeply buried paleosol, and 3) a randomly spaced set. The set of near-surface horizontal fractures is essentially ubiquitous in the upper few meters of all cores in fine-grained materials. In silt, horizontal fracture planes are smooth and parallel (Table 1, site 1) and in till they are rough and less parallel (many sites) (see Fig. 6). The distance between horizontal fracture planes increases with depth from about 0.3 cm to 1.5 cm (0.1-0.6 inch) and they may be cross-cut by vertical and angled fractures (Table 1, sites 4, 5, 10, and 16). The near-surface set of horizontal fractures is generally open and the apertures decrease with depth. Near-surface horizontal fractures are deeper in ridge moraines than ground moraine (Table 2), a trend that tracks with depth of water table and depth of wintertime freezing front. In the two lake-plain cores (sites 1 and 2) which are just 4.6 m (15 ft) apart, near-surface horizontal fractures were either entirely absent (at site 2, 1.46 m [4.8 ft] of medium-grained beach sand halted their development within the sand and in the fine-grained materials below) or they are the deepest of all 24 cores (Table 1, site 1, 3.66 m [12 ft] in silt and till). These two sites

FIGURE 5. Vertical fractures and horizontal fracture polygons in Darby Till at the Molly Caren Agricultural Center, Madison County. (a) Two vertical fractures, 1.0 m (3.3 ft) apart, on a vertical face. Both fractures connect to a horizontal bench in the lower third of the photo (at 1.86 m [6.1ft] depth) where they form a polygon. The light-colored square area above the knife is a secondary precipitate on the face of another fracture that intersects the pit wall. Knife is 23 cm (9 inches) long. Photo by George Hall, The Ohio State University. (b) Several variously sized fracture polygons on a horizontal surface at 1.86 m (6.1 ft) depth. The largest visible here is 1.3 m (4.3 ft) across a diagonal. A light-colored precipitate lines the fracture surface. Photo by George Hall, The Ohio State University. (c) Close-up of a vertical fracture at 1.5 m (4.9 ft) that has air-dried for 4 days. Note light-colored precipitate and the rough fracture trace. Coin's diameter is 1.8 cm (0.7 inches). Photo by Lynn Elfner, Ohio Academy of Science.

TABLE 1

Site and fracture characteristics of central and northern Ohio till cores.

a* site #	b DGS core #	c geomorphic setting	d core T/ DT (m)	e fracture-host lithology	f till unit	g fracture depth (m)	h fracture geom	i fract open or closed	j comments
1	3051	LP	17.72/30.50	silt	NA	0.92-1.59	h	closed	silt w/ smooth, regular horiz fracture surfaces, 0.3-0.5 cm apart
				cl-si till	Hsv or uMb	1.59-3.66	h	NE	faint horiz fractures w/ irregular subhoriz surfaces, 0.5-1.5 cm apart; spacing increases w/ depth
				cl-si till	Hsv or uMb	8.85-8.97	a	closed	several low-angle fractures, 1 cm apart
				si-loam diamict	NA	10-10.25	a	closed	low-angle shear fractures, 0.5 cm apart, small fragments of silt dragged along fractures
				silt	NA	10.58	a	closed	high- and low-angle shear fractures
				cl-loam diamict	NA	10.86-13.36	a	closed	shear fractures, low-angle (top of interval) to high-angle (bottom)
				silt	NA	13.88-14.12	a	closed	high-angle shear fractures
2	3052	LP	17.7/30.5	sand	NA	0-1.46	NA	NA	no fractures in sand
				diamict	NA	9.03-9.27	a	closed	numerous low-angle shear fractures which pinch and swell; 0-1 cm spacing
				cl-loam diamict	NA	10.07-10.49	a	closed	as above
				cl-si till	Hsv or uMb	10.71-12.99	a	closed	numerous low angle fractures which pinch and swell, 0.3-1.0 cm
				cl-loam diamict	NA	12.99-14.09	a	closed	interval w/small sheared silt inclusions
				silt	NA	15.34	a	closed	shear zone w/small voids between brecciated clasts
3	3299	GM	3.39/3.39	cl-si till	Hi, Hsv & uMb	0.52-2.38	h	open	shallow core; numerous fractures, spacing increases downward from 0.5 to 1 cm
				cl-si till	uMb	2.99	v	NE	vert fracture in 3rd till unit
4	3289	GM	9.03/13.42	cl-si till	uMb	0.58-2.41	h	open	irregular fracture surfaces about 0.5 cm apart throughout interval
				cl-si till	uMb	2.14	v	NE	fracture w/ reduced center and oxidized rim
				cl-si till	uMb	2.44	h	closed	single fracture
				loam till	lMb	8.24	a	closed	2 low angle fractures, 0.5 cm apart
5	3292	GM	3.29/3.66	cl-si till	Hi or Hsv	0.46-2.1	h	open	irregular fracture surfaces 0.3-1.0 cm apart; reduced; some fractures with Mn coating
				cl-si till	uMb	2.29	v	NE	
				cl-si till	uMb	2.84	a or h	closed	single fracture
6	3290	GM	10.98/18.91	cl-si till	Hsv & uMb	0.46-3.29	h	open	irregular fracture surfaces 0.7-1.5 cm apart; fracture surfaces oxidized
				cl-si till	uMb	3.97	v	NE	
7	3285	GM	12.96/16.17	cl-si till	Hsv	0.61-2.44	h	closed	irregular fracture surfaces 0.5-1.5 cm apart; fracture surfaces oxidized
				cl-si till	Hsv	2.75	v	NE	
8	3298	GM	9.33/18.30	cl-si till	Hsv & uMb	0.15-1.68	h	open	irregular fracture surfaces about 1.0 cm apart
				cl-si till	uMb	2.84	a	closed	several intersecting low-angle fractures, not reduced, which intersect reduced vert fracture
				cl-si till	uMb	4.42	v	NE	
				cl-si till	uMb	4.82-4.91	a	open	3 low-angle fractures within interval w/ many short openings along them
				cl-si till	uMb	5.30	a	closed	several low-angle fractures, 1 cm apart
9	3041	GM	7.32/12.20	cl-si till	Hsv or uMb	0.25-1.74	h	NE	numerous fractures w/ surfaces about 0.5 cm apart
				cl-si till	mMb	5.10	v	NE	numerous vert fractures

TABLE 1 (*Cont.*)

Site and fracture characteristics of central and northern Ohio till cores.

a* site #	b DGS core #	c geomorphic setting	d core T/ DT (m)	e fracture- host lithology	f till unit	g fracture depth (m)	h fracture geom	i fract open or closed	j comments
10	3042	GM	7.02/12.2	cl-si till	Hsv or uMb	0.46	a	closed	single low-angle fracture among horiz fractures
				cl-si till	Hsv or uMb	0.31-1.59	h	open	most fractures closed near 1.5 m depth
				cl-si till	Hsv or uMb	1.86	a or h	open	single fracture
				cl-si till	Hsv or uMb	2.93	a	closed	high-angle fracture
				cl-si till	Hsv or uMb	3.42	h	NE	single fracture, oxidized
				cl-si till	Hsv or uMb	3.80	v	NE	coating of Mn and gypsum crystals on fracture
11	3043	GM	1.59/12.20	cl-si till	Hsv or uMb	0.25-1.37	h	NE	shallow core; numerous fractures w/ surfaces 0.5-1 cm apart
				loamy diamict	NA	1.53	v	NE	$CaCO_3$ coatings on fracture
12	3044	GM	8.57/12.20	cl-si till	Hsv or uMb	0.25-1.89	h	NE	numerous fractures, spacing increases downward from 0.3 to 1 cm
				cl-si till	Hsv or uMb	2.84	v	NE	Fe, Mn coatings on fractures
				cl-si till	Hsv or uMb	3.66	v	NE	sand- and gypsum-filled fracture
				cl-si till	Hsv or uMb	3.45-3.72	h	NE	several fractures w/ surfaces up to 1 cm apart
13	3045	GM	5.00/12.20	silt	NA	0.25-0.64	h	NE	numerous fractures w/ closely spaced surfaces in soil zone
				cl-si till	Hsv or uMb	0.64-2.59	h	open	numerous fractures w/ faint Fe stains and surfaces up to 1 cm apart; apertures thin w/ depth
				cl-si till	Hsv or uMb	2.84	v	NE	CaCO3 coatings on fracture
				cl-si till	Hsv or uMb	3.39-3.42	v	NE	fracture intersected by 2 low-angle fractures
				cl-si till	Hsv or uMb	3.39-3.42	a	closed	2 low-angle fractures in interval, both intersect vertical fracture
14	3286	GM	6.59/10.98	cl-si till	Hsv	0.61-2.32	h	closed	fractures faint
				cl-si till	Hsv	2.84	v	NE	
				cl-si till	uMb	6.28	h	closed	several fractures not parallel (pinch)
15	3291	GM	14.73/14.73	cl-si till	Hsv	0.92-2.23	h	open	irregular fracture surfaces, spacing about 1 cm
				cl-si till	Hsv	3.81	h	closed	irregular fracture surfaces, spacing about 0.5 cm
				cl-si till	Hsv	3.97	v	NE	
				cl-si till	Hsv	4.64	h	open	single fracture
16	3296	GM	5.80/6.41	cl-si till	Hi & Hsv	0.15-2.59	h	open	irregular fracture surfaces, spacing about 1 cm
				cl-si till	Hsv	2.75	v	NE	
17	3294	RM-St. Johns	14.43/14.43	cl-si till	uMb	1.07-2.59	h	open	irregular fracture surfaces, spacing 0.3-1.0 cm
				cl-si till	uMb	3.05	h	closed	single fracture, irregular surface
				cl-si till	uMb	3.05	v	NE	
				cl-si till	uMb	4.88	a	closed	single high-angle fracture
18	3295	RM-St. Johns	11.71/11.71	cl-si till	Hi & Hsv	0.27-2.14	h	open	irregular fracture surfaces
				cl-si till	Hsv	3.81	v	NE	
				cl-si till	uMb	5.06	h	open	single irregular fracture, oxidized surface

TABLE 1 (*Cont.*)

Site and fracture characteristics of central and northern Ohio till cores.

a*	b	c	d	e	f	g	h	i	j
site #	DGS core #	geomorphic setting	core T/ DT (m)	fracture-host lithology	till unit	fracture depth (m)	fracture geom	fract open or closed	comments
19	3297	SM-Broadway	16.32/16.87	cl-si till	Hsv	0.15-2.65	h	open	irregular fracture surfaces, spacing 0.5-2.0 cm
				cl-si till	uMb	3.81	v	NE	
				cl-si till	uMb	4.88	v	NE	Fe on fracture
				cl-si till	uMb	6.86	a	closed	2 fractures, dip about 30 degrees, about 1.5 cm apart
				cl-si till	uMb	7.50	v	NE	CaCO3 coating on fracture
				cl-si till	uMb	7.78	h	closed	2 fractures 0.7 cm apart
20	3046	EM-Powell	21.05/21.05	cl-si till	Hi & Hsv	0.31-3.05	h	open	irregular fracture surfaces
				cl-si till	Hsv or uMb	5.80	v	NE	Fe, Mn coatings on fractures
				loam till	lMb	14.95-15.01	a or h	closed	fractures pinch and swell, spacing about 1.0 cm; in paleosol
21	3047	EM-Powell	22.11/22.11	cl-si till	Hi	0.25-1.83	h	NE	numerous fractures w/ surfaces up to 1 cm apart
				cl-si till	Hsv or uMb	3.54	h	NE	single fracture
				cl-si till	Hsv or uMb	5.55	a	closed	long axis of pebble aligned along low angle fracture
				cl-si till	Hsv or uMb	5.83	v	NE	Fe, Mn coatings on fractures
				si-loam till	uMb or mMb	12.69-12.99	h	closed	numerous fractures pinch and swell, 0.3-1.0 cm apart; faint Fe stains on fractures; paleosol
				si-loam till	uMb or mMb	13.42-14.03	h	closed	numerous fractures pinch and swell, 0.3-1.0 cm apart; faint Fe stains on fractures; paleosol
				loam till	lMb	15.40	h	closed	several faint fractures pinch and swell, about 1.0 cm apart; paleosol
22	3048	EM-Powell	21.69/21.69	cl-si till	Hi & Hsv	0.31-2.44	h	open	irregular fracture surfaces
				cl-si till	Hsv or uMb	3.05	v	NE	visible joint termination, Fe stain
				cl-si till	Hsv or uMb	4.58	v	NE	3 parallel fractures
				loam till	lMb	13.21	h	closed	faint fractures; in paleosol
23	3049	EM-Powell	8.54/21.35	cl-si till	Hi & Hsv	0.98-2.47	h	open	numerous fractures, 0.2-1.3 cm apart; openings less frequent and thinner with depth
				cl-si till	Hsv or uMb	2.90	v	NE	vert fracture intersected by horiz and low-angle fractures
				cl-si till	Hsv or uMb	3.36	v	NE	two parallel fractures
				cl-si till	Hsv or uMb	4.12	v	NE	Fe coating on fracture
24	3050	EM-Powell	2.71/21.35	cl-si till	Hi	1.07	h	NE	single fracture w/ CaCO3 coating; shallow core
				cl-si till	Hi	0.25-1.95	h	NE	numerous fractures w/ surfaces 0.7-1 cm apart; clay coatings on fractures
				cl-si till	Hsv or uMb	1.95	v	NE	Fe and CaCO3 coatings on fractures

*Column explanations:

a) Sites 1 and 2 are 4.6 m (15 ft) apart, sites 9-13 are 9.2 m (30 ft) apart, sites 20-24 are 4.6 (15 ft0 apart. b) Cores are permanently housed at the Ohio Division of Geological Survey (DGS) and are available for study. c) LP = lake plain, GM = ground moraine, EM = end moraine, RM = recessional moraine, SM = superposed moraine. d) Core thickness/drift thickness at the core site; drift thickness estimated from DGS bedrock-topography maps. e) Lithology in which fractures are developed; cl = clay, si = silt. f) Till units, youngest to oldest: Hiram (Hi), Hayesville (Hsv) Tills (Late Wisconsinan); upper Millbrook (uMb), middle Millbrook (mMb), and lower Millbrook (lMb) tills (Illinoian). h) Fracture geometry, h = horizontal (0-10°), v = vertical (80-90°), a = angled (11-79°), NA = till unit not applicable. i) A fracture is considered open if it appears gaped under a hand lens. Gaping may be natural or may occur during drying or splitting of the core; NE = not evaluated, NA = not applicable.

FIGURE 6. Near-surface horizontal fractures in oxidized till at site 1, 1.80 m (5.8 ft) below the surface. Fracture faces are mostly subparallel and about 0.7 cm (0.3 inches) apart, some pinch and swell. Near-surface horizontal fractures were evident in all cores on the till plain to a depth of about 3 m (10 ft). Photo by C. S. Brockman, Ohio Dept. of Natural Resources, Division of Geological Survey (DGS).

exemplify the effect of unconsolidated lithology on near-surface fracture development. The near-surface set of horizontal fractures are similar to those documented in the freeze-thaw experiment of Benson and Othman (1993) at Madison, WI. The authors consider the near-surface set of horizontal fractures in the cores to be caused by freeze-thaw processes that began in the Pleistocene and continue today.

Another set of high-frequency horizontal fractures was identified in a buried oxidized zone (part of a paleosol) in the top of the lowest till unit (lower Millbrook till) at sites 20, 21, and 22, which are within 4.6 m (15 ft) of each other. The fractures are especially well developed at site 21, where iron-stained horizontal fractures span a 2.71 m (8.9-ft) zone and share many characteristics with the set of near-surface horizontal fractures. The authors consider these fractures to be the result of freeze-thaw activity when the lower till was at the surface during the Illinoian age.

The randomly spaced set of horizontal fractures consist of a single to a few closely spaced fractures that generally occur in the dense tills of the lower stratigraphic units (upper, middle, and lower Millbrook tills). They are present at one or two elevations in 25% of the cores and are rarely open. They are absent in the lake plain cores; however, in the till plain cores they extend 5.13 m (16.84 ft) below the bottom of the near-surface set (see Table 3). The authors consider randomly spaced horizontal fractures that are not associated with high-frequency horizontal fractures to be related to lodgement or glacial ice loading/unloading processes.

Vertical fractures are among and below horizontal fractures, and, like horizontal fractures, their frequency decreases with depth. Vertical fractures are shallower on ground moraine than on ridge moraine, where hilly, dry sites are more common (Table 2). They are absent in the cores on the lake plain. The depths of vertical fractures reported here are shallow compared to elsewhere (6.0 m [20 ft]; see McKay and others 1993) because values from several shallow cores and cores with missing intervals were included in the data analysis (Table 1, sites 3, 5, 11, and 24). Also, cores, unlike large, deep excavations, only rarely encounter the deepest, infrequent fractures. Within a small area, the observed maximum vertical fracture depth in cores varies about 30% (Table 1, sites 9-13 and 20-24). Vertical fractures may penetrate multiple till units (Table 1, sites 3, 8, and 19). No vertical fractures were observed in paleosols or buried oxidized zones (Table 1, sites 20, 21, and 22). Vertical fractures were not evaluated as open or closed in this report. The authors consider

TABLE 2

*Deepest occurrence of fractures in cores from common geomorphic settings.**

geomorph	horizontal fractures, near surface set				vertical fractures				angled fractures			
setting	mean (m)	STD (m)	range (m)	# of cores	mean (m)	STD (m)	range (m)	# of cores	mean (m)	STD (m)	range (m)	# of cores
GM	2.10	0.58	1.37-3.29	14 of 14	3.25	0.97	1.53-5.10	14 of 14	4.96	1.70	2.93-8.24	4 of 14
RM,EM,SM	2.38	0.40	1.82-3.05	8 of 8	4.56	1.77	1.95-7.50	8 of 8	5.75	1.00	4.88-7.78	3 of 8
LP	3.65	NA	NA	1 of 2	NA	NA	NA	0 of 2	14.73	0.86	14.12-15.34	2 of 2

*See Table 1 for abbreviations; STD = standard deviation.

TABLE 3

*Fracture depth of the set of randomly-spaced horizontal fractures.**

site #	geomorphic setting	depth of random h (m)	deepest near-surface set (m)	depth below near-surface set (m)
10	GM	3.42 & 4.82	1.59	1.83 & 3.23
12	GM	3.45-3.72	1.89	1.56 & 1.83
14	GM	6.28	2.32	3.96
15	GM	3.81 & 4.64	2.23	1.58 & 2.41
18	RM,EM,SM	5.06	2.14	2.92
19	RM,EM,SM	7.78	2.65	5.13

*See Table 1 for abbreviations.

vertical fractures in the cores to be components of fractures that are polygonal in plan view and have developed by desiccation processes.

Angled fractures span a greater range of depths than other types of fractures. They are found near the ground surface (Table 1, site 10) and to a depth of 15.34 m (50 ft) (Table 1, site 2). Very few (5%) appear open (Table 1, site 8). Low-angle fractures are much more common than high-angle fractures, perhaps because, in part, the centimeter-scale irregularities of some horizontal fractures may have been misidentified as low-angle fractures. Pebbles and soft-sediment clasts may be aligned along some angled fractures (Table 1, sites 1, 2, and 3). Angled fractures are common at depth in both of the lake plain cores (Table 1, sites 1 and 2) (see Fig. 7). The fractures in the lake plain cores are at similar depths, suggesting they span at least 4.6 m (15 ft), the distance between the cores. They are developed in a complex diamict between stratigraphically lower lacustrine silts and an overlying till. Such a sequence has been interpreted to be caused by ice overriding, grounding, and then incorporating proglacial lake sediments of an ancestral Lake Erie (R. R. Pavey 2000, personal communication). On ground moraine, only 4 of 14 cores contained angled fractures, which, like horizontal and vertical fractures, were shallower than those on ridge moraines (see Table 2). The cores on ridge moraines were the only ones drilled at or near bedrock. There, angled fractures were 9.53 m (31.3 ft) or more above bedrock, seemingly reflecting an absence of shear related to drag along bedrock. Angled fractures were found in all till units but were concentrated above the lowest till unit. The authors consider angled fractures in the cores to result from shearing processes.

DISCUSSION

The Facies, Landscapes, and Physiography of Fractures

A useful way of generalizing the distribution of fractures in till is by relating models of fracture formation, where possible, to types of till materials and then to local geomorphic setting or regional physiography. Of the three basic geometric types of fractures in till—horizontal, parallel high- to low-angle, and polygonal (vertical)—the first two are found in particular facies of till. Basal till may contain horizontal fractures that form as a consequence of the lodgement process. These fracture planes may be lined with sand due to removal of fine materials. The set of characteristics that have been used to differentiate lodgement (basal) till from other till facies (basal melt-out and surface melt-out) are open to interpretation. However, the most diagnostic lodgement characteristics, in addition to horizontal fracture planes, include a relatively uniform pebble fabric, high bulk density, stratigraphic position below melt-out type facies, and glaciotectonic features such as sheared till matrix, and nontill beds thrust into the till matrix (Dreimanis 1989). Lodgement facies have been assumed to be almost universally present under melt-out facies, especially in areas well behind an ice margin where ice thickness was great enough to induce lodgement processes in basal glacial debris. Lodgement facies have been identified in many of the named till units of Ohio; however, there are few studies of their distribution. In the Ohio cores, only two lodgement characteristics are identifiable: dense till and randomly spaced horizontal fractures. These characteristics alone do not confirm the presence of lodgement till, although the assumption that it is relatively common at depth is still viable.

Horizontal fractures also may form by processes that are independent of till facies. They may arise from stress

FIGURE 7. Two high-angle fractures (upper left) intersected by a horizontal fracture in clay-loam diamict at site 1, 10.86 m (35.6 ft) below the surface. Photo by C. S. Brockman, DGS.

release as a consequence of changes in soil volume (from desiccation or thermal expansion/contraction), unloading from erosion, or ice unloading. Information provided by core analysis suggests that horizontal fractures related to freeze-thaw processes may be pervasive. Soil scientists commonly recognize these fractures in the C horizon of many modern soils throughout the state and call them horizontal partings or cleavages (Tornes and others 2000). Their distribution is related to geologic material (they are absent in thick, coarse grained materials), topography (they are deeper on rolling sites), and ultimately physiography. Compared to the relatively flat ground moraine of the Till Plains, near-surface horizontal fractures are deeper in well-drained regions having a lowered ground water table that is characteristic of hummocky or dissected high-relief uplands, such as most sections within the Glaciated Allegheny Plateaus. Such regions also have potential for deeper polygonal (vertical) fractures (Fig. 8). There is potential for an absence of near-surface horizontal fractures in thick surficial sands that are common in several regions of the state, including the kames and eskers of the Akron-Canton Interlobate Plateau and the Mad River Interlobate Plain (Fig. 1, physiographic regions 11 and 3.4), beach ridges and sand sheets of the Maumee Lake Plains (region 7, especially 7.2), and outwash trains (Fig. 8).

Systematic or uniformly trending high- to low-angle fractures are almost always of glaciotectonic origin in Ohio and result from shear displacement by active ice of previously deposited unconsolidated materials and bedrock. (Neo-tectonic fractures from earthquakes, for example, have not been documented in Ohio.) Systematic or parallel shear fractures are considered more prevalent in ridge moraines where glacial ice has undergone regional compression (Moran 1971). Shear fractures trend relative to former ice flow, and surface traces commonly parallel nearby ridge moraines but may diverge under the influence of former local ice and topographic conditions. However, sweeping assumptions about the vertical and lateral extent of ice-thrusting features may be unfounded. For example, Totten (1969) has found that most end moraines in northern Ohio are superposed and the till unit at the base, which is most likely responsible for the landform, is different than the till unit at the surface. Shearing related to end-moraine emplacement in a lower till may not extend into an upper till. For example, in the Broadway Moraine at site 19 (Table 1), which is a superposed ridge moraine, angled fractures are evident in a middle till unit (upper Millbrook till) but not in the lowest unit (lower Millbrook till). In fact, very few angled fractures were observed in any central Ohio ridge moraine. The Ohio literature presently distinguishes among recessional, superposed, and end moraines, but an analysis of topographic types suggests that even within a single moraine, there are many more subdivisions and many more developmental mechanisms. Besides physiographic factors, former local conditions may strongly influence glaciotectonic deformation. Deformation styles may be ductile (folding), brittle (thrusting, faulting, and fracturing), or plastic (dilation or intrusion of soft sediments) and depend on factors such as sediment type, water content, and temperature at the time of deformation (frozen or unfrozen).

At this time, mapping suggests there may be portions of a few ridge moraines in Ohio that have a theoretical potential of being more affected by glaciotectonic shearing than other moraines. These are portions of the relatively large, strongly trending end moraines that form the southern boundary of Ohio's major Wisconsinan till sheets (see Fig. 2). Besides defining the terminus of an ice advance, portions of these end moraines include glaciotectonites (intact thrust blocks that have been moved short distances and imbedded in till) (K. E. Miller 1999, personal communication) and bedrock cores. Lacking more direct evidence, the association between parts of these end moraines and increased frequency of shearing is tentative and a worthwhile direction for further research.

Glaciotectonic shearing not related to moraine development has been active in many areas of the state. Shears within glacially overridden silt/clay diamict and lacustrine materials in the Maumee Lake Plains have been

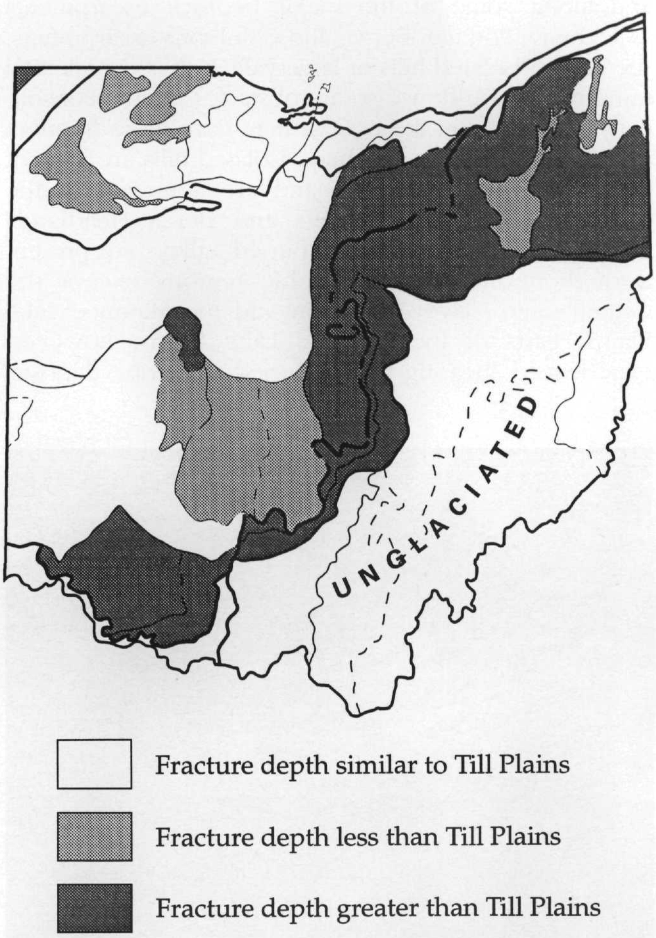

FIGURE 8. Predicted relative depth of near-surface horizontal fractures and vertical (polygonal) fractures in physiographic regions as compared to those in the Till Plains (regions 2 and 3, Fig. 1). Deeper horizontal and vertical fractures are found within better-drained regions and older regions. Fractures are more likely to be absent in regions with common, thick, surficial sand and gravel. See Fig. 1 for explanation of physiographic units.

discussed already (Table 1, sites 1 and 2). Another example of glaciotectonic shearing is a spectacularly large piece of bedrock (glaciotectonite) about 0.4 ha (1 acre) in area which was removed from an isolated hill by Illinoian-age ice and imbedded in the till of the Fort Ancient area of Warren County (Wolford 1932). Smaller, car- and desk-size glaciotectonites of bedrock or paleosols have been observed in till outcrops in Hamilton County (Brockman 1983) (Fig. 9), Clinton County (K. E. Miller 1999, personal communication), Erie County (R. R. Pavey 1999, personal communication), Franklin County (Fernandez and others 1988), and northeastern Ohio (Moran 1971; Ryan 1980). Glaciotectonic features in Ohio are subtle and their geomorphic expression has not been identified to date; however, in Saskatchewan, surface glaciotectonic features in till cover as much as 10% of the province (Christiansen and Whitaker 1976).

Obstacles such as bedrock escarpments and dissected topography are physiographic factors that impede glacial flow and cause compression and shear fractures within glacial ice and the susceptible materials that underlie it (Moran 1971). In Ohio, these physiographic factors are present primarily in the Bellefontaine Upland, the hilly Glaciated Allegheny Plateaus (Szabo and Totten 1992), and along some of the major bedrock escarpments (Allegheny, Portage, Berea, and Columbus escarpments; see Fig. 1). Isolated hills or large valleys that are oriented transverse to ice flow also are obstacles, and unconsolidated sediments in these areas may have more frequent shear fractures than elsewhere. Isolated hills are present throughout glaciated Ohio and are abundant in the Woodville Lake Plains Reefs and Berea Headlands physiographic regions. Major buried valleys are present throughout most physiographic regions except the Central Ohio Clayey Till Plain and the Maumee Lake Plains. Parts of the Maumee Lake Plains, however, experienced shearing within buried lacustrine deposits that were overridden by an ice advance (see Fig. 7). Several regions that have potential for few shear (angled) fractures are those with relatively thick Pleistocene lacustrine deposits that were not overridden by glacial ice, such as the Paulding Clay Basin, Grand River Finger-Lake Plain, and the unnamed lacustrine basins within the Central Ohio Clayey Till Plain (Fig. 10).

FIGURE 9. A glaciotectonite of slightly dipping limestone and shale bedrock imbedded in Illinoian-age till in the Cincinnati area. Bedrock was sheared only a few decimeters (feet) from its original location; closely spaced parallel shear fractures are visible on the horizontal bedrock surface in the creek. The outcrop is about 1.2 m (4 ft) high. Photo by C. S. Brockman, DGS.

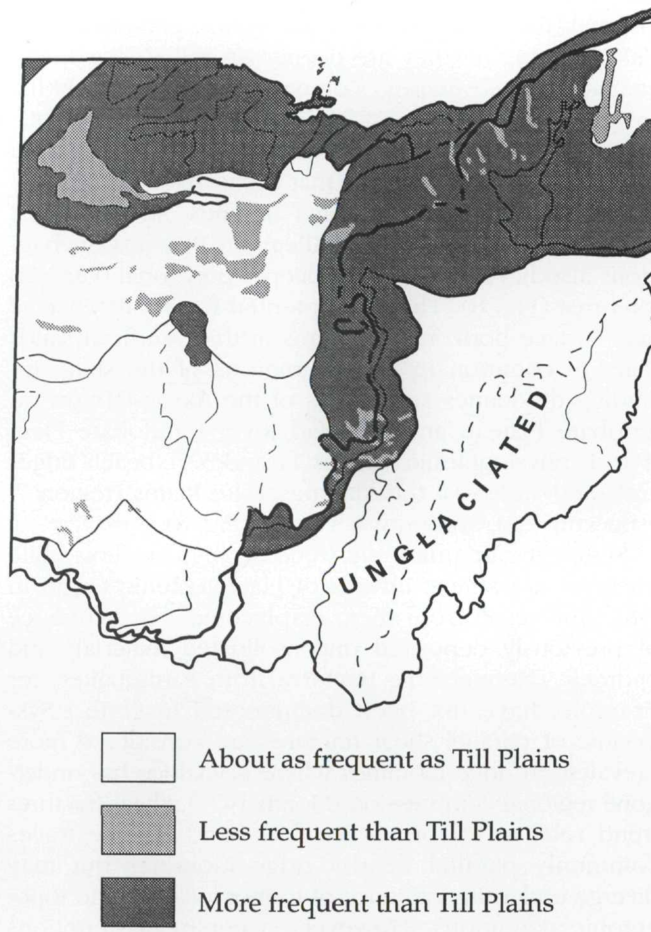

FIGURE 10. Predicted relative frequency of angled fractures in physiographic regions as compared to those in the Till Plains (regions 2 and 3, Fig. 1). Angled fractures are more frequent in regions with high relief, bedrock escarpments, common buried valleys, and lacustrine deposits that have been overridden by ice. These fractures are less frequent in regions with lacustrine deposits that were not overridden by ice, such as the Grand River Finger-Lake Plain. See Fig. 1 for explanation of physiographic units.

Polygonal fractures are common near-surface fractures in Ohio. In the flat areas of the Till Plains, the longest vertical sides of polygons may extend to a depth of 6.0 m (20 ft). In especially dry, high-relief areas, vertical dimensions may be limited only by the height of the slope. For example, the bare till bluffs along Lake Michigan at Racine, WI, are fractured from the surface to the base of the 40 m (130 ft) cliffs. The fractures show characteristics of age in that they are oxidized and contain secondary precipitate; they also extend into the bluff an unknown distance (Weatherington-Rice 1995). The distance must be much greater than the yearly cliff-erosion distance, which averages 1.3 m/yr (4.0 ft/yr). It may be reasonable to assume that even vegetated, dry, steep slopes, such as in the Glaciated Allegheny Plateaus and the Dissected Illinoian Till Plain, are likely to have longer polygonal fractures than similar-aged tills in the low-relief Till Plains. Desiccation and fracturing were probably heightened in the Till Plains of Ohio during the dry Altithermal period (about 6,000 to 9,000 years ago) when prairies and grasslands of the Plains expanded eastward to central Ohio. There are no Ohio studies of the geographic area of a lowered ground water table; however, the Allegheny Escarpment and its slight orographic effect may serve as a logical eastern boundary of regional soil desiccation and the moderately deep (6.0 m [20 ft]) polygonal fractures that resulted from it (see Fig. 8).

Local stratigraphy may have a drying effect on till. Unsaturated sand and gravel underlying till may allow desiccation fractures to propagate through the till more easily. Discrete till bodies in the upper parts of sand and gravel aquifers, which are common within the outwash trains of the Great and Little Miami Rivers of southwestern Ohio, may be fractured from desiccation processes. Lastly, desiccation and stratigraphy may determine some types of fracture coatings. McBurnett and Franzmeier (1997) suggest that clay coatings form along fractures in calcareous till that connect and drain to underlying outwash, whereas carbonate coatings form along those fractures that are undrained (Ryan 1980).

Because of their age, polygonal fractures in pre-Wisconsinan areas (Fig. 2) are better developed and more readily visible than those north of the Wisconsinan glacial margin. In older tills, oxidation rinds on either side of fractures are more pronounced and more resistant to erosion; in stream bottoms they commonly stand in slight relief above the unoxidized matrix (Fig. 11). Some paleosols that may be preserved in the upper surface of pre-Wisconsinan tills are fractured like modern soils. Most paleosols, however, occur relatively near an ice margin in southern Ohio where basal glacial erosion was minimal. Paleosols are rare elsewhere in the state but have been identified in local areas protected from glacial erosion (Table 1, site 21; see Szabo 1997; Hall 1992).

Different types of fractures and shears may intermingle at particular sites. For example, a near-surface lodgement till that has depositionally related horizontal fractures and parallel high-angle shears may contain polygonal fractures as well. Weatherington-Rice (1998) documented such a site near Tremont City in west-central Ohio.

FIGURE 11. Fracture polygons in Illinoian-age till in the Cincinnati area. The polygons are seen through stream water and a light coating of gravel and silt. Vegetation grows within the fractures and an oxidation rind at least 6 cm (2.4 inches) wide stands slightly above the unoxidized interior of the polygon. Hoe-pick is 0.67 m (26.5 inches) long. Photo by C. S. Brockman, DGS.

CONCLUSIONS

The presence of fractures in unconsolidated materials is greatly underacknowledged in the geologic literature for Ohio, and is mentioned only incidentally, if at all, in most reports of Ohio's Quaternary geology. Nevertheless, fractures have been reported from at least one locality in the majority of glaciated Ohio counties (54% or 37 of 68 counties). No studies cite an absence of fractures in an area.

The mechanics of fracture formation in till can be modeled following principles applied to rock. In the field and in cores, fractures in till can best be described by their geometry rather than assumed genesis because similar-appearing fractures can be formed by more than one geologic process. For example, horizontal fractures can form both by freeze-thaw processes and horizontal shear in basal tills.

The most common surface and near-surface fractures, polygonal (vertical) and horizontal, decrease in frequency with depth until they are absent between 3.0 and 6.0 m (10-20 ft). However, fractures that have formed by loading, shearing, or lodgement processes may be present both above and below these depths. Fractures also may be present on and below buried surfaces.

If fractures are not ubiquitous, they are at least very common in all glaciated regions of Ohio. The Till Plains, like other physiographic regions, are fractured in all ways possible. However, more than other regions, it was affected by heightened desiccation. The Lake Plains in Ohio contain a stratigraphic sequence of silt and overlying till that may extend over large areas in the subsurface and host a widely occurring zone of shear fractures. Regions that have a concentration of thick, coarse-grained materials at the surface (notably outwash trains and parts of interlobate areas) will lack near-surface horizontal fractures (see Fig. 8).

Bedrock topography has affected till deposition in the Glaciated Allegheny Plateaus more than any other physiographic section in Ohio. From a theoretical standpoint, local compression induced in glacial ice by bedrock hills would have been more prevalent in the Glaciated Allegheny Plateaus than elsewhere, as would the induced shears in underlying bedrock and unconsolidated materials (see Fig. 10). These shears, which originally formed well below surface deposits, may now be exposed in deep stream cuts and offer additional avenues for water movement.

Generalizations applied to physiographic regions, while not applicable to particular sites, are useful for regional studies of aquifer recharge, pollution potential, and gas migration, to name a few. However, when considering a particular site, a useful generalization to make is that the probability of finding fractures of some type at some depth is relatively high.

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